Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/5650--08-9167

Comparison of the Noise Penalty of a Raman Amplifier Versus an Erbium-doped Fiber Amplifier for Long-haul Analog Fiber-optic Links

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December 17, 2008

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
17-12-2008

2. REPORT TYPE
Memorandum

3. DATES COVERED *(From - To)*
27-02-2008 – 16-04-2008

4. TITLE AND SUBTITLE

Comparison of the Noise Penalty of a Raman Amplifier Versus an Erbium-doped Fiber Amplifier for Long-haul Analog Fiber-optic Links

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Preetpaul S. Devgan, John F. Diehl, Vincent J. Urick, and Keith J. Williams

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory, Code 5652
4555 Overlook Avenue, SW
Washington, DC 20375

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/5650--08-9167

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
One Liberty Center
875 North Randolph St.
Arlington, VA 22203-1995

10. SPONSOR / MONITOR'S ACRONYM(S)

ONR

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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15. SUBJECT TERMS
Analog photonics
Optical amplification
Microwave photonics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL	14	Preetpaul S. Devgan
					19b. TELEPHONE NUMBER *(include area code)* (202) 767-9553

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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- The noise penalty for each amplifier at a given photocurrent is measured and compared.
- An analytical expression comparing the analog metrics as a function of noise penalty and photocurrent for different amplifiers is derived and used.
- The Raman amplifier has a lower noise penalty performance for a long-haul analog fiber-optic link versus an erbium-doped fiber amplifier placed at the end of the link.
- The best compromise comes from a hybrid amplifier, which combines the Raman amplifier with the erbium-doped fiber amplifier and offers the best RF performance while taking only a minimal penalty on the RF noise figure and spurious free dynamic range.

Manuscript approved November 26, 2008.

COMPARISON OF THE NOISE PENALTY OF A RAMAN AMPLIFIER VERSUS AN ERBIUM-DOPED FIBER AMPLIFIER FOR LONG-HAUL ANALOG FIBER-OPTIC LINKS

1 INTRODUCTION

Long-haul analog fiber-optic links are useful for different applications such as antenna remoting [1] and delay lines [2]. Fiber-optic links have been shown to offer increased performance in these applications [3]. Whether these links use either intensity modulation with direct detection (IMDD) [4] or phase-modulation with interferometric detection (ΦMID) [5], they require optical amplification to compensate for the loss of the optical fiber. Erbium-doped fiber amplifiers (EDFAs) have been the amplifiers of choice for these applications, since they offer the advantages of low optical noise figures and high efficiency [6].

While EDFAs have been the common choice for optical amplification of analog fiber-optic links, other amplification techniques exist. While some are lumped, like semiconductor optical amplifiers, others are distributed. A distributed amplifier is one that amplifies over the entire link and not at one contained point. Raman amplifiers are the most commonly used example of a distributed amplifier. Based on a nonlinear optical process, the amplifier uses the fiber of the link as the amplifying medium. Raman amplifiers have also been shown to have lower RIN performance when compared to EDFAs [7], while requiring fewer optical components than an EDFA.

When using optical amplification in a long-haul analog link, the generated noise is the limiting factor in the RF metrics. Recently, a noise penalty metric was derived in order to directly calculate the degradation of the various analog metrics as compared to shot-noise limited performance [8]. The noise penalty also allows us to compare different amplifiers in order to determine which one is better for the application in need.

In this report, we compare the noise penalty for an EDFA as compared to a Raman amplifier for a single 14 km-long analog link. Section 2 provides a derivation that compares the various analog metrics as a function of the difference in noise penalty between each amplifier. Section 3 shows the 14 km-long link with an EDFA and Raman amplifier in order to measure the analog metrics for each configuration. A summary of the work appears in Section 4.

2 DERIVATION OF CHANGE IN ANALOG METRICS FOR DIFFERENT AMPLIFIER'S NOISE PENALTY

In order to properly build amplified optical links, the added noise due to the optical amplifiers has to be measured and then related to the penalty incurred on the performance of the link. Optical noise figure is the commonly used metric for determining the overall performance of amplified links. Since the noise figure is a measure of the degradation of the signal-to-noise ratio (SNR), it is directly relatable to the Q-factor and bit error rate (BER) of digital signals. However, for analog links, the optical noise figure does not directly predict the performance penalty on the analog metrics. Specifically the RF noise figure (NF_{rf}) and spurious-free dynamic range (SFDR) of the link cannot be easily predicted from the optical noise figure. Instead, the noise penalty metric has been developed in order to aid in the design of analog optical links. The noise penalty metric for long-haul analog links have been derived for single amplifiers [9] as well as multiple

cascaded amplifiers [10]. In order to compare the analog performance of links with different amplifiers, we need a way to see how the various RF metrics change for different noise penalties. When using a low relative intensity noise (RIN) laser, the dominant noise source in unamplified links is due to the shot-noise. Using the RIN formalization, the shot noise is defined as

$$RIN_{shot} = \frac{2e}{I_{dc}}, \tag{1}$$

where e is the elementary charge constant, and I_{dc} is the dc photocurrent. From Eqn. 1, we can now define the NF_{rf} in terms of RIN_{shot} as [9]

$$NF_{rf} = \frac{RIN_{shot} V_\pi^2}{\pi^2 k_B T Z_{in}}, \tag{2}$$

where V_π is the required voltage at the Mach-Zehnder modulator (MZM) for a π-phase shift, k_B is Boltzmann's constant, T is the temperature and Z_{in} is the input impedance. The third harmonic SFDR, $SFDR_{3h}$, is also defined as a function of RIN_{shot} as

$$SFDR_{3h} = \left(\frac{12}{RIN_{shot}}\right)^{2/3}. \tag{3}$$

With these definitions in hand, the noise penalty (NP) can now be used to show how the analog metrics are affected by the noise of the amplifiers. The RF noise figure and the SFDR in an amplified link are given by [10]

$$NF_{rf,amp} = NP \cdot NF_{rf} \tag{4}$$

$$SFDR_{3h,amp} = \frac{SFDR_{3h}}{NP^{2/3}}. \tag{5}$$

Even though the RF gain (G_{rf}) is not dependent on the noise penalty of the amplifier, the expression is given by [9]

$$G_{rf} = \frac{I_{dc}^2}{V_\pi^2} \pi^2 Z_{in} Z_{out}. \tag{6}$$

The RF gain is provided here as it illustrates the improvement in this metric is directly proportional to increased dc photocurrent, which is directly proportional to the optical power. Since higher optical power amplifiers typically have higher noise penalties, the trade-off of RF gain and the other metrics is an important one to consider.

In order to compare two different amplifiers, we define the noise penalty of amplifier #1 as NP_1 and the noise penalty of amplifier #2 as NP_2. We will also consider that the output power of the amplifiers is different. The dc photocurrent due to amplifier #1 is listed as $I_{dc,1}$ and due to amplifier #2 as $I_{dc,2}$. We also assume everything else is the same when comparing the two amplifiers. The RF gain is the first analog metric that will change for different amplifiers. The ratio of RF gain between both amplifiers can be written from Eqn 6 as

$$\frac{G_{rf,1}}{G_{rf,2}} = \frac{I_{dc,1}^2 V_\pi^{-2} \pi^2 Z_{in} Z_{out}}{I_{dc,2}^2 V_\pi^{-2} \pi^2 Z_{in} Z_{out}} = \frac{I_{dc,1}^2}{I_{dc,2}^2} \,. \tag{7}$$

From Eqn. 7, one can see the RF gain is purely a function of the dc photocurrent and the higher the dc photocurrent, the higher the RF gain. The increase in the RF gain is balanced by an increase in the noise which can affect the RF noise figure and the SFDR. Starting with the RF noise figure expression in Eqns. 2 and 4, the ratio of noise figures can be expressed as

$$\frac{NF_{rf,1}}{NF_{rf,2}} = \frac{\dfrac{RIN_{shot,1} V_\pi^2}{\pi^2 k_B T Z_{in}}(NP_1)}{\dfrac{RIN_{shot,2} V_\pi^2}{\pi^2 k_B T Z_{in}}(NP_2)} = \frac{RIN_{shot,1} NP_1}{RIN_{shot,2} NP_2} = \frac{I_{dc,2} NP_1}{I_{dc,1} NP_2} \,. \tag{8}$$

From Eqn. 8, the ratio of the RF noise figures is dependent on the noise penalty and the dc photocurrent. The improvement in the noise figure due to increased photocurrent is now tempered by the higher noise penalty that comes with the increased power from the optical amplifier. Finally from Eqns. 3 and 5, the SFDR ratio is expressed as

$$\frac{SFDR_{3h,1}}{SFDR_{3h,2}} = \frac{\left(\dfrac{12}{RIN_{shot,1} NP_1}\right)^{2/3}}{\left(\dfrac{12}{RIN_{shot,2} NP_2}\right)^{2/3}} = \left(\frac{RIN_{shot,2} NP_2}{RIN_{shot,1} NP_1}\right)^{2/3} = \left(\frac{I_{dc,2} NP_2}{I_{dc,1} NP_1}\right)^{2/3} \,. \tag{9}$$

We now have expressions comparing the SFDR, RF noise figure and RF gain as functions of both the noise penalty and the dc photocurrent due to different amplifiers. No assumption has been made about which type of amplifier has been used for the previous derivations. Thus, we can use these equations to compare a Raman amplifier to an EDFA.

3 EXPERIMENTAL SETUP AND RESULTS

In order to compare the two amplifiers, the configuration of the link has to be designed. Starting with the laser, we chose a distributed feedback (DFB) laser with ~80 mW output power (EM4 EM253). This laser was chosen as its measured RIN is below that of the shot-noise level [11], which is one of the requirements from the derivation in section 2. Since our derivation in section 2 assumed the use of an MZM to impose the RF signal on the optical carrier of the laser, we chose to use the IMDD architecture over the ΦMID. Choosing the IMDD architecture also simplifies the receiver end of the link as we can use a single photodetector at the RF output. The 14 km length of fiber was chosen as it allows for the Raman amplifier to provide enough gain to overcome the loss of the fiber span as well as providing a fairly high Stimulated Brillouin Scattering (SBS) threshold. Finally we need to decide on the placement of the amplifier.

Since the EDFA is a lumped amplifier, it can be placed anywhere in the link. It is often easier to place the amplifier at the beginning or end of the link as this combines all the associated electronics and dc power with the transmitter or the receiver. Because the input power is often limited by the SBS threshold in long fiber links, combined with the fact that the laser has sufficient output power, the EDFA does not need to be placed at the beginning of the fiber. Thus the optimal placement for the EDFA is after the fiber span and before the photodetector.

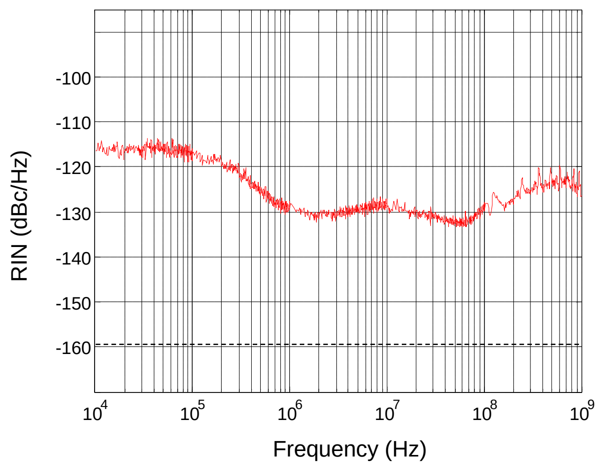

Fig. 1. RIN spectrum of a co-pumped Raman amplifier.

The Raman amplifier is a distributed amplifier; it uses the nonlinear Raman scattering process in the optical fiber of the link to provide gain to the signal. The Raman amplifier requires a high power pump laser to access the gain from the Raman scattering process. The pump for the Raman amplifier can be placed at either the beginning or the end of the link in order to get the most gain from the link. Placing the pump at the transmitter makes the Raman amplifier into a co-pumping configuration, meaning the pump and the signal to be amplified travel in the same direction in the link. Placing the pump at the receiver makes the Raman amplifier into a counter-pumping configuration, meaning the pump travels in the opposite direction of the signal to be amplified. The difference in the configurations depends on the noise of the Raman pump. Since the Raman scattering process occurs on the femtosecond time scale, the RIN from the pump laser will impose itself on the signal laser in the co-propagating configuration. This will increase the RIN at the output of the link. In the counter-propagating configuration, the RIN of the pump is averaged over the entire link, minimizing the amount of RIN added to the signal laser. In order to determine how large a detriment the added noise is, the RIN at the output of the link was measured in a co-propagating Raman amplifier configuration. The results are shown in Figure 1. The measured RIN is much higher than the shot noise limit. Since the RIN is at its lowest still 28 dB higher than the shot noise, we cannot use the co-propagating Raman pump configuration. Therefore we will use the counter-propagating Raman amplifier configuration.

The final setup is shown in Figure 2. The output of the DFB laser is connected to either a variable optical attenuator (to measure RIN) or an MZM with a V_π of 5.3V at 1 GHz (to measure RF gain and OIP3). A polarization controller is then used to co-polarize the laser with the Raman pump. The polarization controller is important as the Raman amplifier is polarization dependent. If the signal and pump are not co-polarized, the gain is not optimal and in fact will become close to zero when the signal and pump are cross-polarized. The light is then fed into 14 km of LEAF fiber followed by a photodiode (DSC 50S). The output of the photodiode is connected to an electrical spectrum analyzer (ESA) in order to measure the RF metrics. Note that an RF amplifier is included after the photodiode when measuring the RIN of the amplifiers.

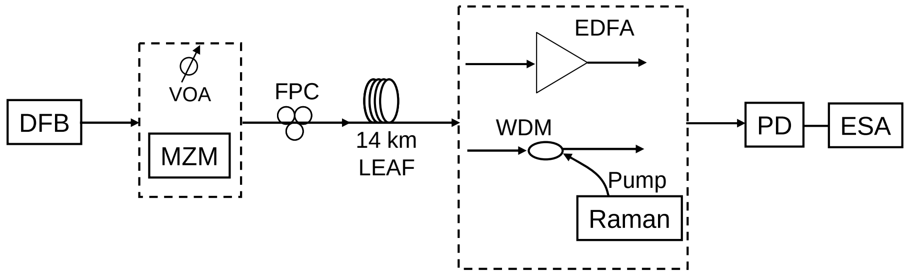

Fig. 2. Final setup for the EDFA and Raman amplifier comparison. VOA: variable optical attenuator, DFB: semiconductor laser, MZM: Mach-Zehnder modulator, FPC: fiber polarization controller, WDM: wavelength division multiplexer, PD: photodiode, ESA: electrical spectrum analyzer.

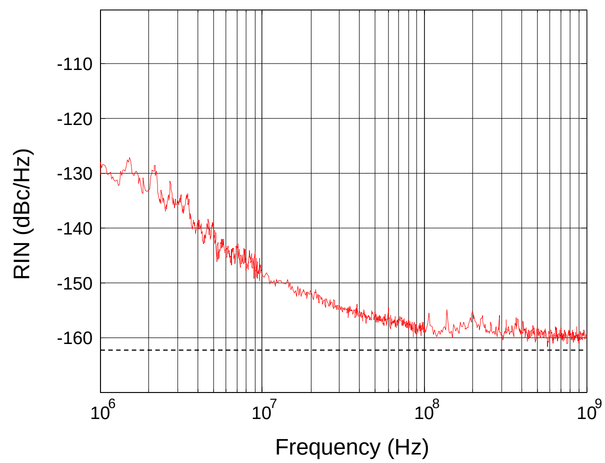

Fig. 3. RIN spectrum for counter-pumped Raman amplifier at a photocurrent of 5.5 mA.

3.1 RIN measurements for EDFA and Raman amplifiers

As seen in section 2, the RF metrics depend on the dc photocurrent. While we have access to many different EDFAs, we only have one type of Raman pump. The Raman pump allows us to compensate the loss of the fiber to less than 1 dB. Since the SBS threshold of the 14 km of fiber reduces by ~2.5 dB when the Raman pump is on, the maximum output power at the end of the fiber link is 8.4 dBm, which at the photodetector yields a dc photocurrent of 5.5 mA. The two EDFAs we compared were an in-house designed and built one and a commercial one (PriTel FA-18). Since both EDFAs have high gain and moderate output powers, we can operate them to yield much higher photocurrents at the photodiode. Therefore, to compare the Raman amplifier to the EDFAs, we measured the RIN of the EDFAs at 5.5 mA as well as at 10 mA.

The RIN measurement for the Raman amplifier appears in Figure 3. The dotted line shows the shot-noise RIN level for a photocurrent of 5.5 mA. The large RIN from 1 MHz to 100 MHz is due to a couple of external sources: 1) the phase noise of the laser is converted into RIN by the dispersion of the long fiber link and amplified, as can be seen in the 20 dB/decade slope of the RIN and 2) operating at the SBS threshold injects extra noise at low frequencies which is also amplified. At 1 GHz, the external noise sources are negligible and we can determine the noise penalty. The measured RIN is -160 dBc/Hz and the shot-noise RIN is -162.4 dBc/Hz.

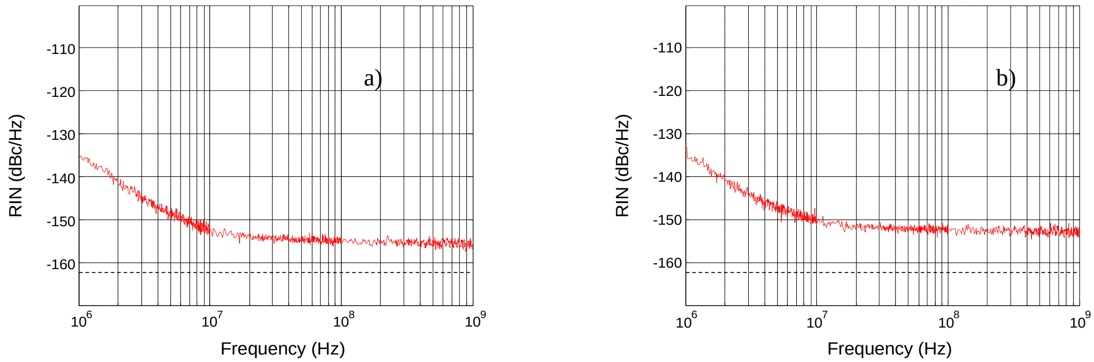

Fig. 4. RIN spectrums for a) in-house and b) commercial EDFAs operating at a photocurrent of 5.5 mA.

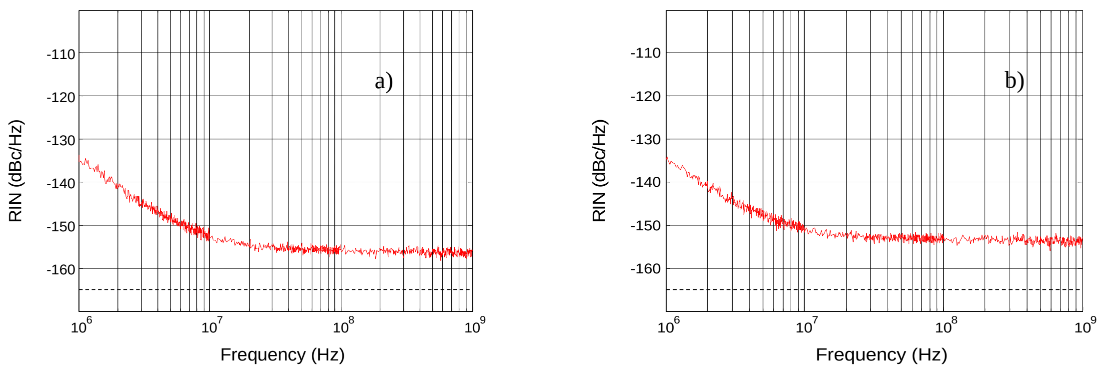

Fig. 5. RIN spectrums for a) in-house and b) commercial EDFAs operating at a photocurrent of 10 mA.

For comparison, the measured RIN for the in-house built and commercial EDFA are shown in Figures 4 a) and b), respectively. Again the noise at low frequencies is evident, meaning it is due to a common source not limited to just the Raman amplifier. The measured RIN for the in-house and commercial EDFAs is -155.8 and -153 dBc/Hz, respectively. The shot-noise RIN is the same for all three cases, -162.4 dBc/Hz. Clearly the EDFAs have more noise than the Raman amplifiers for the same dc photocurrent. However since the EDFAs can operate at higher photocurrents, perhaps the additional noise will not degrade the RF metrics.

In order to determine how the RF metrics will compare for the different amplifiers at higher photocurrents, the RIN was measured after the EDFAs' drive currents were increased to reach a photocurrent of 10 mA. The measured results are shown in Figures 5 a) and b). The shot noise RIN is marked as a dashed line at -165 dBc/Hz. The measured RIN for the in-house and commercial EDFA is -156 and -154 dBc/Hz. Since the input power to the EDFAs remains the same as from the previous operating condition, the increase in optical power has led to an increase in generated RIN from the amplification process. How this increase in RIN affects the RF metrics is discussed in the next section

3.2 Noise penalty comparison for EDFA and Raman amplifiers

In order to calculate the noise penalty of the various amplifiers, we must define the NP in terms of the shot noise RIN and the amplifier RIN. Using the following relations [10],

$$RIN_{measured} = RIN_{sig-sp} + RIN_{shot} \tag{10}$$

$$NP \approx 1 + \frac{RIN_{sig-sp}}{RIN_{shot}} \tag{11}$$

where RIN_{sig-sp} is the noise due to the amplification process, yields an NP of 2.4 dB. Note an NP less than 3 dB is possible since the amplifier does not completely compensate the loss of the fiber link. Using Eqns. 10 and 11 for the in-house and commercial EDFAs, we get an NP of 6.6 and 9.4 dB, respectively. Since the dc photocurrent is the same for all the amplifiers, the RF metrics degrade by the difference in NP. From Eqns 8 and 9, the Raman amplifier has a better RF noise figure by 4.2 and 7 dB and a better SFDR by 2.8 and 4.7 dB over the in-house and commercial EDFA, respectively. The RF gain is the same for all three amplifiers. These improvements are summarized in Table 1.

Table 1. Noise penalty and RF noise figure and SFDR penalty for Raman amplifier at a photocurrent of 5.5 mA and EDFAs at a photocurrent of 5.5 mA.

Amplifier	Noise Penalty (dB)	Penalty in RF NF vs. Raman (dB)	Penalty in SFDR vs. Raman (dB)
Raman	2.4	REF	REF
In-house EDFA	6.6	4.2	2.8
Commercial EDFA	9.4	7	4.7

The next comparison involves running the EDFAs with output powers high enough for 10 mA of photocurrent. The Raman amplifier is already at its maximum output power and so its NP and associated RF metrics stays the same. After adjusting the EDFAs to get 10 mA of photocurrent, the RIN was measured. The results appear in Figures 5 a) and b). The NP for the in-house and commercial amplifier is 9 and 11 dB, respectively. In order to see how this affects the RF metrics, we use Eqns. 7-9 to see how the RF metrics compare to the Raman amplifier. The metrics are listed in Table 2. While the RF gain is 5.2 dB higher with the EDFAs, the RF noise figure is 4 and 6 dB worse for the in-house and commercial EDFAs. The SFDR is 2.7 and 4 dB worse for both amplifiers. Clearly, the improvement in RF gain comes at a price in terms of RF noise figure and SFDR performance. The requirements on the link performance will dictate the use of either an EDFA (for increased RF gain) or a Raman amplifier (for better RF noise figure and SFDR performance) for use in the analog link.

Table 2. Noise penalty and RF noise figure and SFDR penalty for Raman amplifier at a photocurrent of 5.5 mA and EDFAs at a photocurrent of 10 mA.

Amplifier	Noise Penalty (dB)	Penalty in RF NF vs. Raman (dB)	Penalty in SFDR vs. Raman (dB)	Improvement in RF Gain vs. Raman (dB)
Raman	2.4	REF	REF	REF
In-house EDFA	9	4	2.7	5.2
Commercial EDFA	11	6	4	5.2

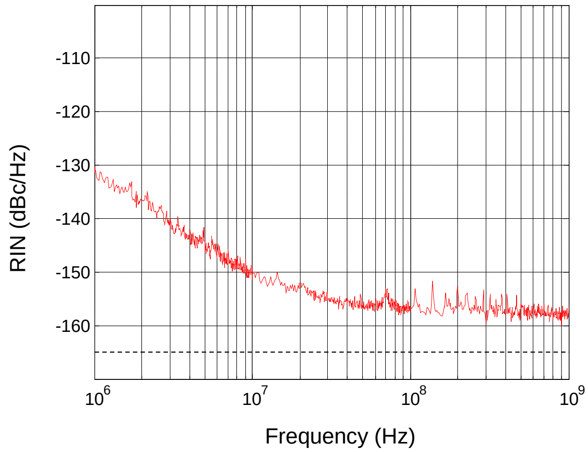

Fig. 6. RIN spectrum for hybrid amplifier at a photocurrent of 10 mA.

A final configuration worth exploring is the combination of a Raman amplifier with an EDFA in order to get the best performance for all the metrics. In this setup, the Raman pump is set in the counter-propagating configuration and the EDFA remains before the photodiode. The Raman pump is still set to give an output power of 8.4 dBm, and the EDFA is set to generate a photocurrent of 10 mA. The in-house EDFA was used as its noise penalty was lower than the commercial amplifier. We refer to this configuration as a hybrid amplifier as it combines two different amplifier technologies. The measured RIN for the hybrid amplifier is shown in Figure 6. The RIN at 1 GHz is -158 dBc/Hz, which gives a noise penalty of 7 dB. Note this noise penalty is 2 dB lower than the EDFA by itself. The RF noise figure for the hybrid amplifier is only 2 dB worse than the Raman amplifier by itself, while the SFDR is only 1.3 dB worse. The improvement in the hybrid amplifier comes from the Raman amplifier allowing a higher input power into the EDFA, which saturates the EDFA and reduces the noise penalty of the EDFA. The results are summarized in Table 3.

Table 3. Noise penalty and RF noise figure and SFDR penalty for Raman amplifier at a photocurrent of 5.5 mA and EDFAs at a photocurrent of 10 mA.

Amplifier	Noise Penalty (dB)	Penalty in RF NF vs. Raman (dB)	Penalty in SFDR vs. Raman (dB)	Improvement in RF Gain vs. Raman (dB)
Raman	2.4	REF	REF	REF
In-house EDFA	9	4	2.7	5.2
Hybrid	7	2	1.3	5.2

As a final note, the DC power consumption of the different amplifiers should be compared. The main power consumption for both the in-house EDFA and the Raman amplifier is the pump laser. While the thermoelectric cooler circuit requires the same current for each of the pumps, the drive current is different. Since the Raman amplifier is based on a nonlinear optical effect, it requires higher optical pump powers. This in turn requires higher drive current for the Raman pump. In our case, the Raman pump requires 850 mA versus the EDFA pump, which requires 200 mA. Since the forward voltage is the same, the DC power consumption of the Raman amplifier is ~4 times as much as the EDFA.

4 SUMMARY AND CONCLUSIONS

Long haul analog fiber optic links continue to serve an important role in different applications. Even with high power, low noise DFB lasers, the SBS in long fiber lengths limits the amount of power that can be passed down these links. Since the analog metrics improve with increased dc photocurrent, optical amplification is often required for long-haul links. While the RIN of the laser is much lower than the shot noise RIN, the RIN due to the optical amplification is above the shot noise RIN and is the dominant noise source. In order to relate the RIN due to the amplifier to the degradation of the RF metrics, the noise penalty was derived. In order to compare different types of amplifiers with different output powers, there was no derivation for how the noise penalty will compare the RF noise figure and SFDR for two different amplifiers. In this report we have derived a set of equations to compare the RF metrics for two different amplifiers with different output powers and noise penalties, and then used these equations to compare a Raman amplifier with an EDFA.

Section 2 presented the derivation of the RF noise figure and SFDR for two different amplifiers. The relationships show that the metrics degrade as the noise penalty increases but that they do not degrade as much if the dc photocurrent, which is directly related to the output power of the amplifiers, increases. This derivation works for any amplifier for which one can measure the noise penalty and dc photocurrent generated at the photodiode.

Section 3 presented an experimental setup to compare three different amplifiers for a 14 km fiber link. A Raman amplifier was compared to two different EDFAs, one in-house designed and built and the other a commercial product. The noise penalty for each of the amplifiers was measured for a dc photocurrent of 5.5 mA and the RF metrics were compared. The EDFAs were then set to generate a dc photocurrent of 10 mA and the noise penalties were again measured and the RF metrics were compared. In the second case, even though the RF gain increased by 5.2 dB for the EDFAs versus the Raman amplifier, the RF noise figure and SFDR were still degraded by 4 and 2.7 dB, respectively, in the best case (in-house EDFA). Finally, a hybrid amplifier combining the Raman amplifier and the in-house EDFA was used and compared to the Raman by itself. In this case, the RF noise figure and SFDR were only degraded by 2 and 1.3 dB, respectively. These results show the noise penalty can be used to compare different amplifiers even when they are operating at different output powers.

In the 14 km link, the best operation was the Raman amplifier in terms of RF noise figure and SFDR, when compared to the EDFAs. However the output power of the Raman amplifier is limited and thus the RF gain cannot be improved. In order to get the best of both worlds, the hybrid amplifier is the best solution. While the RF noise figure and SFDR are worse than in the Raman amplifier case, the reduction is only 2 and 1.3 dB, respectively. In comparison, the RF gain increases by 5.2 dB. Thus, the reduction is easily balanced by the improvement in RF gain.

APPENDIX A LOGARITHMIC EXPRESSIONS FOR NOISE PENALTY COMPARISON

Below are expressions for the comparison of RF gain, RF noise figure and SFDR in logarithmic scale.

$$G_{rf,1}(dB) - G_{rf,2}(dB) = 20 \cdot \log_{10}\left(\frac{I_{dc,1}}{I_{dc,2}}\right). \tag{12}$$

$$NF_{rf,1}(dB) - NF_{rf,2}(dB) = NP_1(dB) - NP_2(dB) + 10 \cdot \log_{10}\left(\frac{I_{dc,2}}{I_{dc,1}}\right). \tag{13}$$

$$SFDR_1(dB) - SFDR_2(dB) = \frac{2}{3}\left(NP_2(dB) - NP_1(dB) + 10 \cdot \log_{10}\left(\frac{I_{dc,2}}{I_{dc,1}}\right)\right). \tag{14}$$

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